SEISMIC VULNERABILITY ANALYSIS OF BASE-ISOLATED STRUCTURES BASED ON RESPONSE SURFACE METHOD

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Abstract

The base isolation technique has been widely used in practical engineerings on account of its advantages in reducing the seismic responses of superstructures. However, due to the randomness of earthquakes and the uncertainties inherited in the structures, base-isolated structures still face a risk of damage under the effect of earthquakes, especially when encountering the earthquakes beyond design levels. Moreover, base isolation devices are prone to become the vulnerable parts under the seismic actions because of the large relative displacement between the superstructure and the foundation. Therefore, it is significant to comprehensively evaluate the seismic risk of base-isolated structures under different seismic levels. While the actual earthquake damage data of the base-isolated structures are limited and cannot provide sufficient statistical information, seismic vulnerability analysis is an effective way to assess the seismic risk of base-isolated structures.

In this paper, the seismic vulnerability of base-isolated reinforced concrete structures is studied and a response surface method (RSM) based simulation approach is proposed, which significantly reduces the workload of nonlinear time history analysis while ensuring the accuracy. Firstly, The maximum inter-story drift ratio of the superstructure and the maximum displacement of the isolation layer are identified as the performance indicators of the base-isolated reinforced concrete structures. Three performance levels and corresponding performance criteria are specified, which are suitable for general base-isolated reinforced concrete structures. Secondly, the uncertainty parameters of the base-isolated structures are characterized. The concrete compressive strength, concrete elastic modulus, and bulk density are identified as the uncertain input parameters of the superstructures. The horizontal yield stiffness and the yield force of lead-rubber bearings are considered as the random variables of isolators. Seismic hazard intensity is measured by peak ground acceleration. Uncertainties from the earthquakes are implicitly incorporated in the analysis by the use of sixty ground acceleration records with a wide variety of seismic hazards. Subsequently, an RSM based procedure to analyze the seismic vulnerability of the base-isolated structures is introduced. The seismic response quantities of the base-isolated structures are approximated by a dual response surface, which incorporates the intensity measure in constructing the response surface. Thereafter, a base-isolated reinforced concrete structure is taken as an example to illustrate the RSM based seismic vulnerability analysis approach. The dual response surface model of the base-isolated reinforced concrete structure is constructed. The failure probability of the base-isolated structure under different seismic levels is calculated and the seismic vulnerability curves are generated. The performance of the base-isolated structures under strong earthquakes is studied and laid special emphasis on. Lastly, the seismic vulnerability of the base-isolated structure is compared to its fixed-base counterpart. The effectiveness and reliability of base isolation are investigated.

Results show that the base isolation technique can significantly reduce the seismic failure probability of the reinforced concrete structures and can effectively prevent the superstructure from entering a serious damage state. Furthermore, the RSM based seismic vulnerability analysis procedure proposed in this paper can significantly improve the efficiency of seismic vulnerability analysis and is of great value in engineering application.

Keywords: Base Isolation; Seismic Vulnerability; Response Surface Method

1. Introduction

The base-isolation technique effectively reduces the seismic response of the superstructure, but due to the large relative displacement between the superstructure and the foundation, the isolation devices are likely to become the vulnerable components under the effect of earthquakes. Moreover, due to the randomness of earthquakes and the uncertainties inherited in the structures, base-isolated structures still face a risk of damage, especially when encountering the earthquakes beyond design levels. Therefore, it is significant to comprehensively evaluate the seismic risk of base-isolated structures under different seismic levels. While the actual earthquake damage data of the base-isolated structures are limited and cannot provide sufficient statistical information, seismic vulnerability analysis is an effective way to assess the seismic risk of base-isolated structures.

The research on the seismic vulnerability analysis of base-isolated structures has attracted more and more attention. Perotti[1] developed a numerical procedure for the computation of fragilities for structural components in base-isolated nuclear power plant (NPP) buildings, adopting dynamic integration, response surface, FORM, and Monte Carlo (MC) simulation method. Saha[2] analyzed the seismic fragility of base-isolated liquid storage tanks using response surface model based MC simulation. Firoozabad[3] estimated the fragility curves of the seismically isolated NPP piping system and verified the numerical results by conducting monotonic and cyclic loading experiments of the identified points. Alhan[4] used the MC simulation technique to determine the reliability of base isolation for the protection of critical equipment. Castaldo[5] evaluated the seismic reliability of a base-isolated structure with friction pendulum isolators, adopting the Latin Hypercube Sampling (LHS) method for random sampling.

In this paper, a response surface method (RSM) based simulation approach is proposed to assess the seismic vulnerability of the base-isolated structures, which can significantly reduce the workload of nonlinear time history analysis while ensuring accuracy. A base-isolated reinforced concrete structure is taken as an example to illustrate the RSM based approach. Both the uncertainty in the structure and the ground motions are considered when constructing the dual response surface model. The failure probability of the base-isolated structure under different seismic levels is calculated and the performance of the base-isolated structures is laid particular emphasis on. Lastly, the seismic vulnerability of the base-isolated structure is compared to its fixed-base counterpart to investigate the effectiveness and reliability of the base isolation technique.

2. Failure criteria for base-isolated buildings

The maximum inter-story drift ratio of the superstructure θ_{max} and the maximum displacement of the isolation layer δ_{LRB} are identified as the demand parameters for base-isolated reinforced concrete structures. Three performance levels and corresponding performance criteria are specified, which are suitable for general base-isolated reinforced concrete structures, as shown in Table 1. Note that θ_{max} at the life safety limit state is 1/3 of the collapse prevention limit state, considering that the inelastic response of the lateral-load-resisting superstructure system is limited to about 1/3 of a comparable, fixed-base building for the design earthquake. The shear deformation γ of the isolation bearings is selected as the acceptance criteria, considering that the shear deformation γ can reflect the damage state of the isolation bearings.

For the non-isolated structures, the limit state function is defined as:

$$g_i(\mathbf{X}) = \theta_i - \theta_{\max}(\mathbf{X}) \tag{1}$$

where $g_i(\mathbf{X})$ is the performance function with respect to the i^{th} limit state, $\mathbf{X}$ is the vector listing the random variables, θ_i denotes the limit of maximum inter-story drift ratio with respect to the i^{th} limit state, $\theta_{\max}(\mathbf{X})$ denotes the maximum inter-story drift ratio.

Table 1 – Performance levels of base-isolated reinforced concrete structures

Demand parameters	**Operational**	**Life Safety**	**Collapse Prevention**
θ_{max}	1/300	1/150	1/50
δ_{LRB}	100% γ	250% γ	400% γ

For the base-isolated structures, the damage state of the isolation layer should also be considered. The limit state functions take the form:

$$\begin{cases} g_i(\mathbf{X}) = \theta_i - \theta_{\max}(\mathbf{X}) \\ g_i(\mathbf{X}) = \delta_i - \delta_{LRB}(\mathbf{X}) \end{cases} \tag{2}$$

where δ_i denotes the limit of maximum displacement of the isolation layer with respect to the i^{th} limit state, $\delta_{LRB}(\mathbf{X})$ denotes the maximum displacement of the isolation layer.

3. Modeling of base-isolated structures

A typical reinforced concrete frame structure is taken as an example to illustrate the RSM based seismic vulnerability analysis approach. The basic seismic design intensity of the reinforced concrete structure is 0.3g. The isolation devices were designed to achieve the performance objective that the basic seismic design intensity of the superstructure can be reduced to 0.15g. Forty-three lead rubber bearings (LRB) were accordingly designed to meet the performance objective. The main mechanical properties of the bearings are shown in Table 2 and the plane layout of the bearings is shown in Fig. 1. The finite element model of the base-isolated structure was established in ANSYS, as shown in Fig. 2, using the COMBIN40 element to simulate isolation bearings and using the BEAM189 element to model beams and columns. The stress-strain relations for concrete is the Mander confined concrete stress-strain model. The constitutive model adopts a multi-stage linear dynamic enhanced elastoplastic model that obeys the von Mises yield criterion.

Table 2 – Mechanical properties of lead rubber bearings

Isolator Type	**Datum Pressure** (Mpa)	**Long-term Load** (kN)	**Vertical Stiffness** K_v(kN/mm)	**Initial Stiffness** K_1(kN/mm)	**Post-yield Stiffness** K_d(kN/mm)	**Equivalent Stiffness** K_h(kN/mm)	**Yield Strength** Q_d(kN)	**Damping** Heq(%)
LRB700	15	5603	3157	14.213	1.093	1.643	76	20.4
LRB800	15	7275	3671	16.447	1.265	2.052	123	23.1
LRB900	15	9202	4260	18.511	1.424	2.337	160	23.5

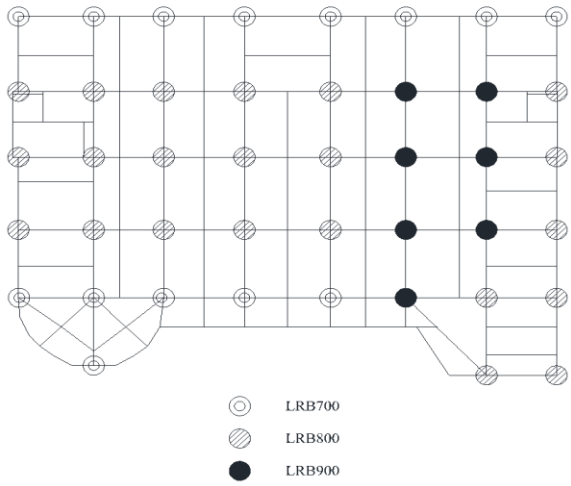

Fig. 1 – The floor plan of isolation bearings

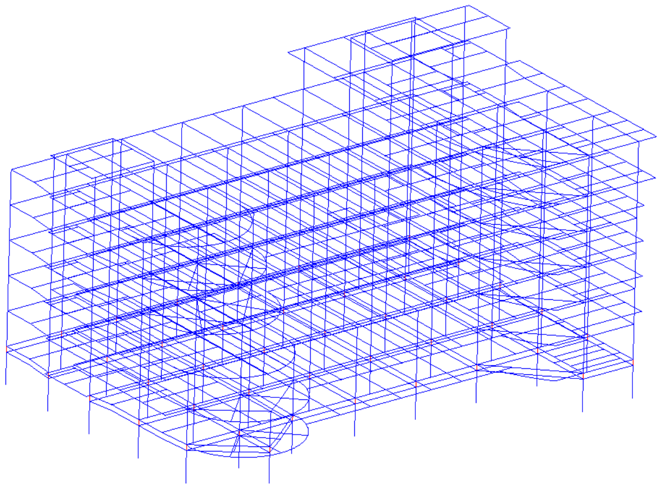
Fig. 2 – ANSYS model of the base-isolated structure

4. Uncertainties in base-isolated buildings

4.1 Uncertainties in structural parameters

The uncertainties of the base-isolated structure are mainly reflected in the strength, stiffness, deformation capacity and energy dissipation characteristics of the structural members. When the nonlinear seismic analysis is used to build a stochastic model, the uncertainty of seismic responses is primarily reflected in the variability of the materials. For the superstructure, the uncertainty of the concrete material is mainly considered. Given that the concrete constitutive model uses the Mander model, the performance of concrete in the elastic phase can be reflected by the elastic modulus E_c and bulk density γ_w, and the performance of concrete in the nonlinear phase can be reflected by the compressive strength $f_{cu,k}$. Thus, the concrete compressive strength $f_{cu,k}$, concrete elastic modulus E_c, and bulk density γ_w are identified as the uncertain parameters of the superstructures.

The initial stiffness K_1, the horizontal yield stiffness K_d, the equivalent stiffness K_h, and the yield strength Q_d are essential parameters to characterize the shear performance of isolation bearings. Among them, the post-yield stiffness K_d and the yield strength Q_d can better characterize the performance of the isolators under major earthquakes. Thus, these two parameters are selected as the random variables of isolators.

Table 3 – Structural uncertainties of base-isolated reinforced concrete structures

Random Parameters		**Mean**	**COV**	**Distribution**
Superstructure	Concrete Elastic Modulus E_c	Initial design value	0.10	Normal
	Bulk Density γ_w	1.050 G_k (Dead Load)	0.10	Normal
Lead Rubber Bearings	Post-yield Stiffness K_d	Initial design value	0.15	Normal
	Yield Strength Q_d	Initial design value	0.15	Normal

According to the results of parameter sensitivity analysis[6], the structural uncertainty parameters that have more significant impacts on the response of the isolated structures are the concrete elastic modulus E_c, the structural bulk density γ_w, the yield strength Q_d and the post-yield stiffness K_d of the isolation bearings. The influence of the concrete compressive strength $f_{cu,k}$ on the displacement of the base-isolated structures can be neglected. Therefore, E_c, γ_w, Q_d and K_d are selected for seismic vulnerability analysis, assuming that the random variables are independent of each other. Statistical descriptions of the random variables are shown in Table 3.

4.2 Uncertainties in earthquake loadings

Previous research has shown that the peak ground acceleration (PGA) provides a high correlation with the structural response of base-isolated structures[7]. As a result, PGA is chosen as a seismic intensity measure in this study and is included in the response surface model as an uncertainty parameter.

In order to fully consider the uncertainties in earthquake loadings, sixty ground acceleration records will be used for seismic vulnerability analysis. Uncertainties from the earthquakes are implicitly incorporated in the analysis by the use of sixty ground acceleration records with a wide variety of seismic hazards. The ground motions are real records from the PEER NGA-West2 ground motion database. The records are selected to meet the following criteria[8, 9]: (1) The epicentral distance is less than 50km; (2) The Richter magnitude of the selected database ranges between 5.5 and 9.0; (3) The site conditions are consistent with the site where the structure is located; (4) Limited number of records coming from the same event to avoid event biasing of the demand estimation. The number of earthquake records required for seismic vulnerability analysis can be reduced as much as possible through a reasonable classification method. Thus, the bin method is adopted to classify and select the ground acceleration records[10]. The Richter magnitude is used as a criterion to distinguish minor and major earthquakes, and the epicenter distance is used to define near and far field earthquakes. The selection range of earthquake records is divided into five bins based on the magnitude and epicenter distance. Twelve earthquakes are chosen for each bin. The median spectral acceleration value for each bin is compared with the response spectrum determined by the Chinese code for seismic design of buildings to ensure that the earthquake records chosen are representative of all earthquakes in each respective bin. The distribution of earthquake records selected by bin method is shown in Fig.3 and earthquake records in the same bin are marked with the same color. The response spectrums of sixty records from NGA-West2 are plotted in Fig.4 and are compared with the response spectrum determined by the Chinese code for seismic design of buildings.

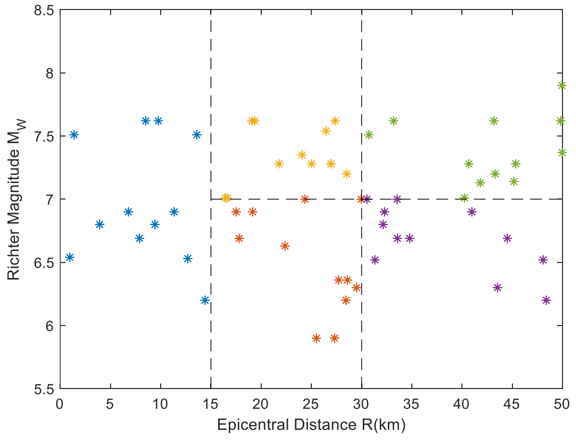

Fig. 3 –The distribution of earthquake records selected by bin method

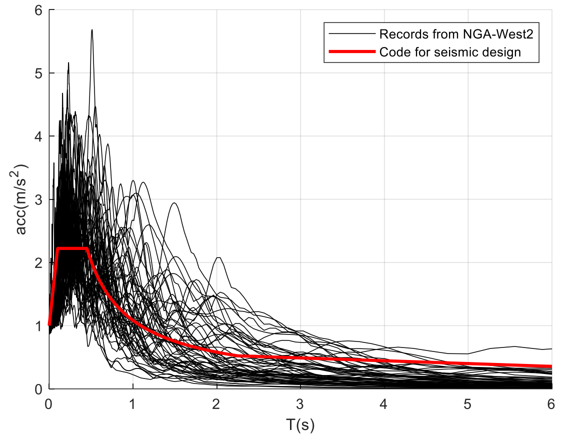

Fig. 4 –The response spectrum of records from NGA-West2 and determined by the code for seismic design

5. Seismic vulnerability analysis of base-isolated structures

5.1 RSM based approach for calculating seismic vulnerability

Seismic fragility is defined as the conditional probability that a structure would meet or exceed a certain damage level for a given level of seismic intensity measure (IM)[2]. Therefore, the generic representation of this conditional probability is given as:

$$F_R(y) = P\left[D \geq C \middle| IM = y\right] \tag{3}$$

where D represents the structural demand, C represents the structural capacity, IM=y denotes the specific level of a selected seismic intensity measure (IM).

In this study, three limit states and corresponding failure criteria are defined for base-isolated structures, so the probability of failure at each intensity level can be expressed in terms of the critical response quantities:

$$PF_{ij} = P\left(LS_i \middle| IM = y_j\right) = P\left(EDP \geq x_i \middle| IM = y_j\right) \tag{4}$$

where PF_{ij} denotes the probability of failure with respect to the i_{th} limit state at the j_{th} IM level, LS_i denotes the i_{th} limit state, EDP is the engineering demand parameter.

Once the probability distributions of random variables $\mathbf{X}=\left(X_1, X_2, \ldots, X_n\right)$ are characterized, the probability of exceeding the limit state can be expressed by the form of the integral:

$$PF_{ij} = P\left(g_i(\mathbf{X}) \leq 0 \middle| IM = y_j\right) = \int_{g_i\left(X \middle| IM = y_j\right) \leq 0} f_{\mathbf{X}}(x)\,dx \tag{5}$$

The integral could be computed by a straightforward Monte Carlo Simulation (MCS) method. However, the MCS method requires a large number of simulations to obtain a reliable estimate of the low probability of failure[11]. Massive computing cost would be paid for base-isolated systems, as the nonlinear time-history analysis is necessary for each simulation. In this study, the response surface method (RSM) in connection with the MCS is explored to evaluate the seismic fragility of base-isolated structures. The basic idea of RSM is to replace the actual limit state function $g(\mathbf{X})$ with a polynomial type of function $\hat{g}(\mathbf{X})$. Here, a quadratic polynomial with cross terms is used as a metamodel representation:

$$\hat{Z} = \hat{g}(\mathbf{X}) = a + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} c_i X_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d_{ij} X_i X_j + \varepsilon \tag{6}$$

where a, b_i, c_i and d_{ij} are the coefficients of the polynomial, n is the number of the variables X and ε is the random error.

In this RSM based approach, the dual response surface concept is introduced[11, 12], assuming that the distribution of building response can be described by its mean value and its standard deviation. The IM is included in the response surface model in addition to the structural uncertainty parameters. Although the random variable of IM will increase the workload of experimental designs, the number of nonlinear time-history analyses will still be significantly reduced, since only one response surface model would need to be fitted. The response surface metamodels for predicting the mean and standard deviation of the structural responses can be expressed as:

$$\hat{y}_\mu = g(\mathbf{x}, IM) \tag{7}$$

$$\hat{y}_\sigma = h(\mathbf{x}, IM) \tag{8}$$

Assuming that the structural response follows a normal distribution, the overall response surface model can be expressed as:

$$\hat{y} = g(\mathbf{x}, IM) + N[0, h(\mathbf{x}, IM)] \tag{9}$$

Subsequently, MCS can be applied to the approximated model to calculate the probability distribution of the structural response.

5.2 Response surface models for seismic response of base-isolated structures

Central composite design (CCD) strategy is utilized as the design of experiments scheme for fitting the RSM. The number of coefficients necessary for CCD is $2^n + 2n + 1$, including one center point, 2^n factorial points, and $2n$ axial points. The initial design center is assumed at the mean values of the random variables $\mathbf{x}_M = (\mu_{X_1}, \mu_{X_2}, \cdots, \mu_{X_n})$. The cube points are selected by a complete 2^n factorial design, namely $(x_{M1} \pm 2\sigma_1, \cdots, x_{Mi} \pm 2\sigma_i, \cdots, x_{Mn} \pm 2\sigma_n)$. Two axial points are selected on the axis of each design variable at a distance of α from the design center $(x_{M1}, \cdots, x_{Mi} \pm \alpha\sigma_i, \cdots, x_{Mn})$. $\alpha = \sqrt[4]{2^n} = \sqrt[4]{2^5}$ is chosen in the CCD method to make the design rotatable. Random variables that define uncertainties in structural properties are normalized to have its range between -1 and +1. The lower bound, center point, and upper bound of the variable PGA are defined as $1.1\,m/s^2$, $3.0\,m/s^2$ and $5.1\,m/s^2$, respectively, corresponding to the basic design acceleration of ground motions by Chinese code for seismic design of buildings. Sixty ground acceleration records are divided into three batches, and the peak acceleration of each batch is scaled to the lower bound, center point and upper bound, correspondingly.

Twenty nonlinear dynamic analyses of the base-isolated structures are carried out at each design point to obtain the maximum inter-story drift ratio of the superstructure θ_{max} and the maximum displacement of the isolation layer δ_{LRB}. Then the mean and the standard deviation values for each peak response quantity are computed at each design point. The number of coefficients necessary to define the polynomials is (k + 1)(k + 2)/2, and the unknown coefficients are determined by the least square regression analysis. The response surface models for the θ_{max} and δ_{LRB} can be expressed as:

$$\hat{y}_{\theta_{max}} = \hat{y}_{\mu_{\theta_{max}}}(PGA) + N\left[0, \hat{y}_{\sigma_{\theta_{max}}}(PGA)\right] \tag{10}$$

$$\hat{y}_{\delta_{LRB}} = \hat{y}_{\mu_{\delta_{LRB}}}(PGA) + N\left[0, \hat{y}_{\sigma_{\delta_{LRB}}}(PGA)\right] \tag{11}$$

The prediction profiler plots of the base-isolated structure for the mean and standard deviation of θ_{max} and δ_{LRB} are shown in Fig.5~ Fig.8. The response is plotted against each of the random variables, while other random variables are held constant, quantifying the influence of all the significant effects.

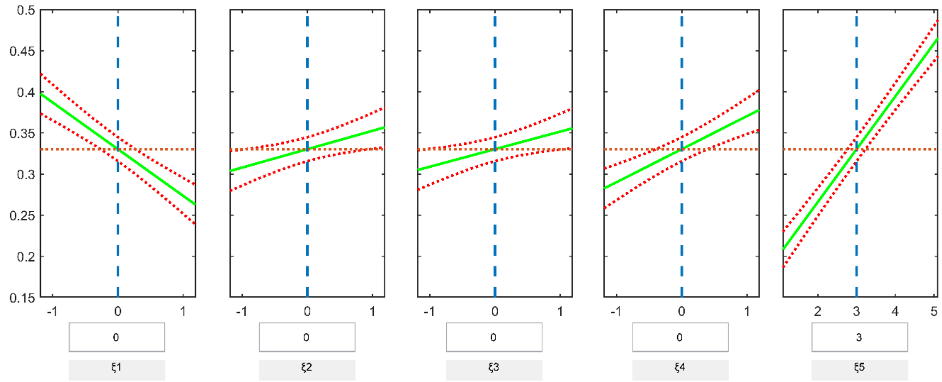

Fig. 5 – Prediction profiler of the mean of maximum inter-story drift ratio

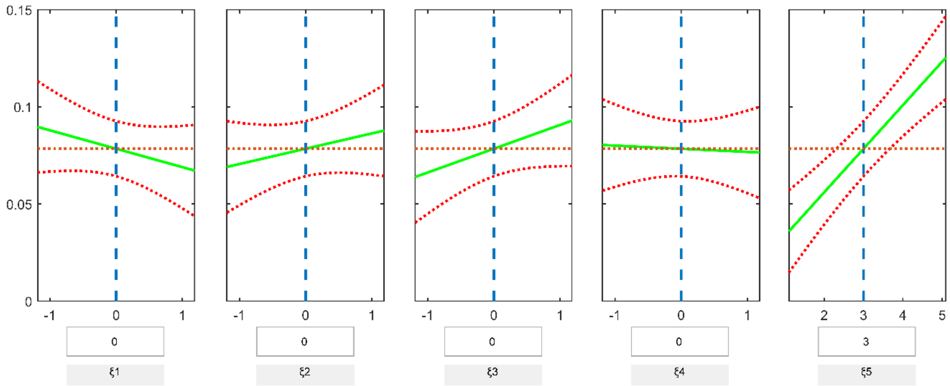

Fig. 6 – Prediction profiler of the standard deviation of the maximum inter-story drift ratio

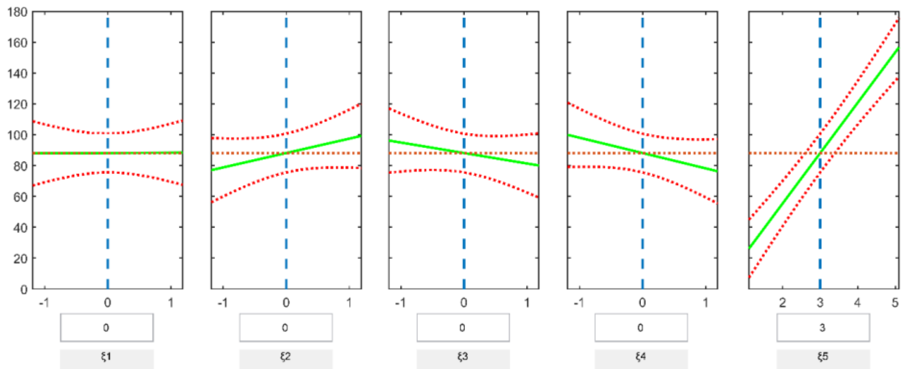

Fig. 7 – Prediction profiler of the mean of maximum displacement of the isolation layer

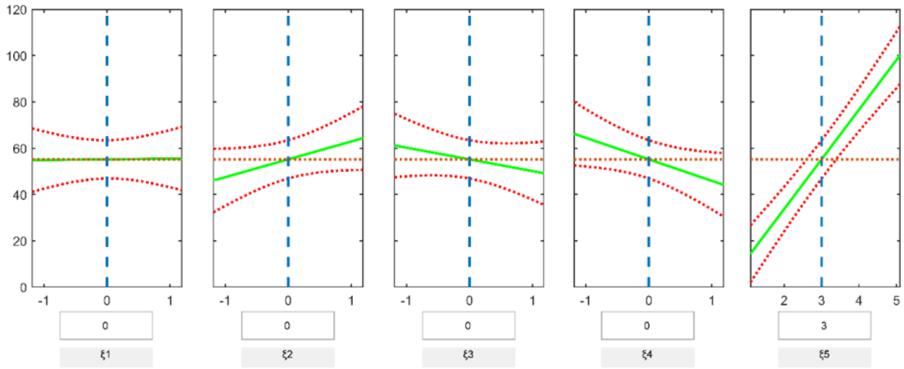

Fig. 8 – Prediction profiler of the standard deviation of maximum displacement of the isolation layer

It can be seen from the prediction profiler plots that the uncertainties within ground motions have a much greater influence on the base-isolated structures than the uncertainties in structural parameters.

5.3 Evaluation of the vulnerability of the base-isolated system

After the response surface model is constructed, the response surface function at a specific intensity level can be obtained. Keeping the PGA constant, 10,000 Monte Carlo simulations are carried out over the metamodels with the randomly generated structural parameters. The base-isolated system is considered as a serial system composed of two components, which are the superstructure and isolation layer. It is judged that the base-isolated system fails when one of the two components exceeds its response limits. Assuming that no correlation between the component demands, the failure probability of the base-isolated system conditioning to a specific PGA level can be computed by the equation[13]:

$$P\left(F_{system}\right)=1-\prod_{i=1}^{m}\left[1-P\left(F_i\right)\right] \tag{12}$$

where $P\left(F_i\right)$ is the probability of failure of component i and $P\left(F_{system}\right)$ is the probability of the base-isolated system. The probabilities of the base-isolated structure exceeding the Operational, Life Safety and Collapse Prevention limit states are shown in Table 4.

Varying the PGA for all earthquake intensity levels, the seismic vulnerability curve of the base-isolated system can be plotted, as shown in Fig.9.

Table 4 – The exceedance probability of the base-isolated structure

Exceedance Probability	P_{LS_1}	P_{LS_2}	P_{LS_3}
PGA=0.1g	0.01	0.00	0.00
PGA=0.3g	0.57	0.00	0.00
PGA=0.5g	0.93	0.11	0.00

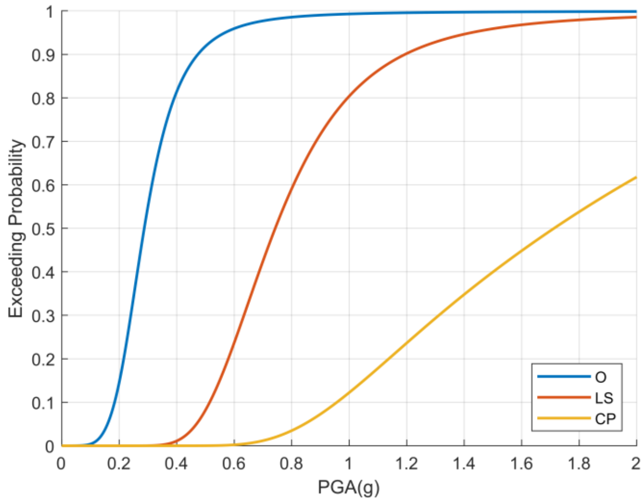

Fig. 9 – Seismic vulnerability curve of the base-isolated system

It can be seen from Table 4 and Fig.9 that there is approximately 1% chance that the damage of the base-isolated structure exceeds the Operational performance level under the intensity level 0.1g (63% in 50 years), and there is virtually no chance that the building will be damaged beyond the Life Safety performance level under the intensity level 0.3g (10% in 50 years) and beyond the Collapse Prevention performance level under the intensity level 0.5g (2% in 50 years). It can be concluded that the base-isolated structure will maintain operational under minor earthquakes, guarantee life safety under moderate earthquakes and prevent collapse under major earthquakes.

6. Comparison of the vulnerability of isolated and non-isolated structures

In order to compare the structural performance of base-isolated and non-isolated structures under different intensity levels, the seismic vulnerability of the non-isolated counterpart is analyzed. The uncertainty parameters of the non-isolated structure selected are the concrete elastic modulus E_c, the structural bulk density γ_w, and PGA. Statistical descriptions of the random variables are the same with the base-isolated structure, and the random variables are assumed independent of each other. Ground acceleration records used for nonlinear analysis are also consistent with the base-isolated structure. The maximum inter-story drift ratio θ_{max} is identified as the demand parameter for fix-based reinforced concrete structures. The seismic vulnerability curve of the fix-based structure is plotted and compared with the seismic vulnerability for the inter-story drift ratio of the base-isolated structure, as shown in Fig.10.

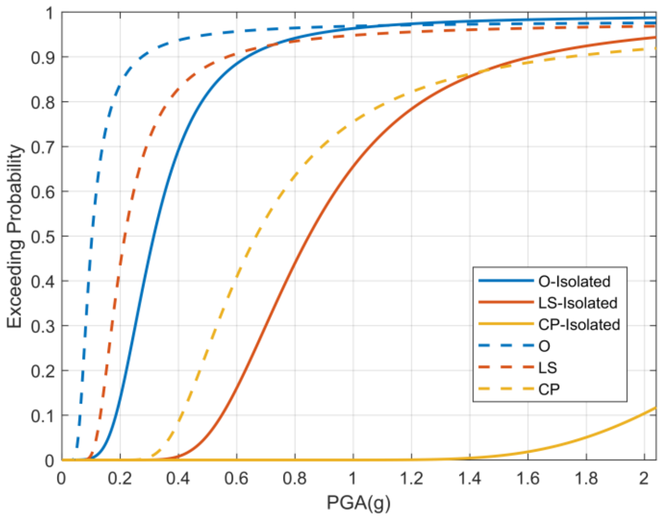

Fig. 10 – Seismic vulnerability curve for the inter-story drift ratio of the fix-based and base-isolated structure

It can be concluded from Fig.10 that the use of seismic isolation technique can significantly reduce the failure probability of structures under different levels of earthquakes. The reduction keeps growing with the increase of PGA, as non-isolated structures suffer more damage under moderate and major earthquakes. Moreover, the reduction of the failure probability is more significant for the higher damage levels, which indicates that the measures of base-isolation can effectively prevent the superstructure from entering a serious damage state.

7. Conclusion

In this study, the seismic vulnerability of base-isolated structures is analyzed based on the dual response surface method. The randomness of the ground motions and the uncertainty of the structures are incorporated in the analysis to build more accurate stochastic models. The seismic performance of the base-isolated structures is evaluated under different levels of earthquakes. The seismic vulnerability of the non-isolated counterpart is also analyzed and compared with the base-isolated structure. The following conclusions can be made.

a. The uncertainties within ground motions have a much more significant influence on the base-isolated structures than the uncertainties in structural parameters.

b. The base-isolated structure will maintain operational under minor earthquakes (63% in 50 years), guarantee life safety under moderate earthquakes (10% in 50 years) and prevent collapse under major earthquakes (2% in 50 years).

c. The use of seismic isolation techniques can significantly reduce the failure probability of structures under different levels of earthquakes and can effectively prevent the superstructure from entering a serious damage state.

d. Using the dual response surface method for seismic vulnerability analysis reduces a lot of complex finite element computing workload, improves the efficiency of seismic vulnerability analysis while ensuring accuracy, and provides high engineering application value.

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